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Diurnal Trends in Wheat Canopy Temperature, Photosynthesis, and Evapotranspiration

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*Remote sensing technology to study vegetative canopies by measuring optical, thermal, and microwave signatures provides optimism for frequent characterization of plant performance in the field. Ground truth data are required in the calibration and the validation of satellite data. The objective of this work was to measure canopy temperature (CT), canopy photosynthesis (CER), and evapotranspiration (ET) of spring wheat (*Triticum durum* Desf. "Aldente") irrigated at two levels. A large portable field chamber (volume of 3.25 m^3 and an area of 2.67 m^2) enclosed the canopy, and CO_2 and water vapor concentrations were measured at 2-s intervals for 60 s with an infrared gas analyzer operated in differential mode. Canopy temperature was measured with an infrared thermometer (4° FOV; 0.15 m dia spot size) mounted on the outside front corner of the chamber aimed 3 m directly in front of the chamber and represents the mean of 15 measurements. Other estimates of CT were obtained from a fixed infrared thermometer at the weather station and from low flying aircraft. Diurnal measurements were completed on 10 April 1989 when the wheat was in midflowering (Zadoks scale 65). Diurnal trends in CER showed differences between fully irrigated and deficit-irrigated plots. The small differences in ET and CT between irrigated and deficit-irrigated plots suggested minimum plant stress on deficit-irrigated plots, at least during the early part of the day. The cumulative daytime photosynthesis showed the irrigated plots averaged 28.9 g CO_2 m^{-2} while the deficit-irrigated plots showed a 52% reduction in CER. The CT ranged from about 7°C near sunrise through a maximum of 27°C and then decreased to 15°C at sundown. The average cumulative daytime chamber ET was 8.41 mm and 7.69 mm for the fully and deficit-irrigated plots, respectively, which compared with reference ET of 8.91 mm and aircraft estimate of 8.93 mm. Diurnal trends in CT and ET showed a stronger association and were similar for both irrigated and deficit-irrigated plots.*

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INTRODUCTION

The increased importance of water use efficiency in agricultural production has prompted the need for techniques to measure evapotranspiration and canopy photosynthesis to evaluate the effects of soil and water management practices. The advent of remote sensing technology to study vegetative canopies by measuring optical, thermal, and microwave signatures provides potential for frequent characterization of plant performance in the field. This new technology has increased the need for high-quality ground truth data for calibration and the validation of satellite data on a unit land area basis.

Measurement of the physical and the physiological characteristics of the plant and the biophysical processes at the earth's surface, such as photosynthesis expressed as carbon dioxide exchange rate (CER) and evapotranspiration (ET), can facilitate the interpretation of remotely sensed data of the surface condition. Canopy or surface temperature is often measured with various remote sensing platforms and can provide some understanding of physiological processes that affect plant performance. Most biological processes are temperature-dependent, and, therefore, measurement of canopy temperature (CT) by thermal infrared radiometry may be an important diagnostic tool of vegetation status. However, interpretation of the biological and environmental significance of CT is considerably more complex than the translation and interpretation of simple temperature measurements. The significiant contributions of Jackson and his co-workers to this area of work is acknowledged (Jackson, 1984; Jackson et al., 1983; 1985; 1987; Moran et al., 1989). A better understanding of the relationship between canopy temperature and photosynthesis should lead to a better understanding of management practices required for increased water use efficiency. Thus there is a need to characterize the diurnal nature of plant canopy temperature and relate it to photosynthesis and evapotranspiration.

Furthermore, a plant canopy consists of many leaves, with a range of temperatures, so that adequate sampling is difficult. Spatial variation due to soil properties and temporal variation due to dynamic microclimate add to the complexity of interpreting crop response to new management practices. The noncontact infrared thermometer enables large spatial averages that may be extrapolated up to large areas and related to data obtained by remote sensing techniques from both aircraft and satellites.

As part of a larger experiment to compare remote sensing technologies, this work was designed to compare techniques for evaluating photosynthesis, water use, and components of the energy balance of wheat (*Triticum durum* Desf cv. Aldente). The specific objective of this work was to measure CER and ET of fully irrigated and deficit irrigated wheat using a portable chamber, and to relate the values to CT measured with infrared thermometers from a portable chamber, from aircraft, and from a fixed weather station.

METHODS AND MATERIALS

The experiment was conducted on Field 3201 of the University of Arizona Maricopa Agricultural Center (latitude 33.075°N and longitude 111.983°W). The field was planted to spring wheat (*Triticum durum* Desf cv. Aldente) on 16 December 1988 and had dimensions of 281 m × 709 m. The soil was a reclaimed Trix sandy loam (fine-loamy, mixed [calcareous], hyperthermic Typic Torrifluvents), a deep, well-drained, very slowly permeable soil. The visual uniformity of the crop across all chamber plots and the entire field suggested little effect of soil differences. The field was fallow the previous year. The wheat was planted at the seeding rate of 224 kg ha^{-1} with a row orientation east / west and a row spacing of 15 cm. Nitrogen was applied at planting at 112 kg ha^{-1}. The wheat had completely developed spikes and with the grain in the watery ripe or blister stage (Zadoks scale 65) on days of measurement. The canopy leaf area index was 4.86 and 3.87 for the fully irrigated and deficit-irrigated wheat, respectively, both treatments having a 1.0-m canopy height (P. J. Pinter, personal communication, 1989). The general appearance of the crop was excellent during the grain filling period.

The locations of the weather station, chamber measurement plots, and aircraft flight line within Field 3201 are shown in Figure 1. The chamber plots were located from 5.5 m on Day 99 to 11.9 m on Day 100 from the south edge of Field 3201 in the southeast corner of each of the individual borders where access was obtained from the field road. The three plots referred to as deficit irrigated were last irrigated on 14 March 1989 (Day 73) with 159 mm of water. The fully irrigated plots representing the well-watered treatments, with presumably no stress, were last irrigated on 2 April (Day 92) with ≈ 160 mm of water. The last significant rainfall for the area was 31 mm on 26 March 1989. Visual differences between deficit-irrigated and fully irrigated plots were not evident at any time during the measurements on Days 99 and 100. Only on the perimeter of the deficit-irrigated plots was there any evidence of slight wilting, which could be attributed to an edge effect.

Gas exchange measurements were made on 9 April (Day 99) and 10 April (Day 100) 1989, using a portable chamber. The portable chamber technique used to measure CER and ET was described by Reicosky and Peters (1977), Peters et al. (1974), Reicosky et al. (1983), Reicosky (1985), and Meyer et al. (1987). A description of the recent improvements and the incorporation of an infrared gas analyzer into the system and the methods of calculating CER and ET for corn and soybean was presented in Reicosky (1990) and Reicosky et al. (1990).

Briefly, the portable chamber was constructed of clear plastic material (Lexan) over a metal frame and was mounted on the front end of a farm tractor. The chamber contained four fans for complete mixing of the air and was mounted on a hydraulic forklift mechanism attached to the front-end loader of a 45 kW farm tractor. The tractor transported the chamber and recording equipment from plot to plot, along with the portable generator that enabled measurements in a remote field location. The tractor, with the portable chamber in the UP position, was maneuvered until the reference points aligned with the reference stakes, and the chamber was lowered over the plots for 60 s with the fans continuously running. Data were collected by a computer-controlled data acquisition system at 2-s intervals; then the chamber was lifted. While the chamber was moved to the next location, the rates of CER and ET were calculated, printed out for immediate analysis and decision-making, as well as the raw and calculated data

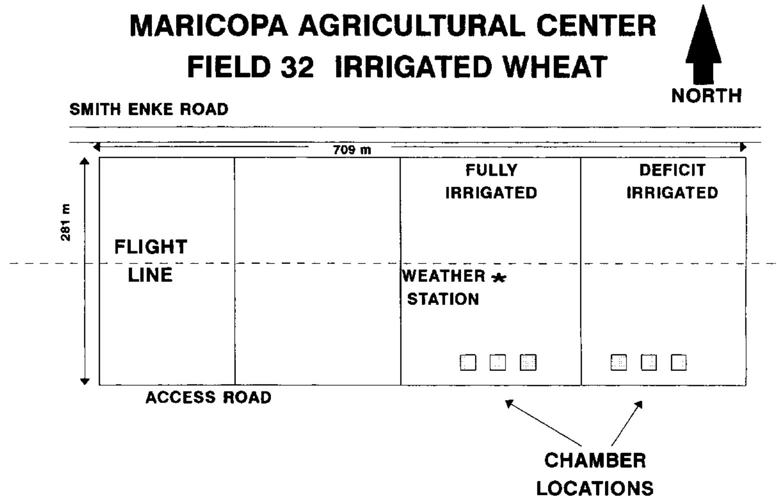


Figure 1. Sketch of Field 32 with relative locations of weather station, aircraft flight line, and chamber plots.

stored on tape for further processing. For each measurement, the time the chamber made contact with the soil, the plot identification, solar radiation (RI), photosynthetically active radiation (PAR), air temperature (TA), and infrared thermometer (IRT_c) data were recorded (Reicosky et al., 1990).

The infrared gas analyzer was a BINOS[1] (Inficon Leyhold-Heraeus, Inc.) dual channel analyzer operating in the differential mode. The analyzer had a range of ± 50 μmol mol^{-1} for CO_2 and ± 5000 μmol mol^{-1} for water vapor and was calibrated for an ambient CO_2 concentration of 372 μmol mol^{-1} and for a dew point temperature of 5°C. Water vapor was separated from the gas sample going through the CO_2 cell of the infrared gas analyzer using a vacuum pump and a Permapure dryer (Model MD-190-48P). Using vacuum, this dryer selectively impeded the transmission of water vapor through the tube so that only dry air went through the infrared gas analyzer on the CO_2 channel. Subsequently, it was noted that dewpoint temperature data at 1 m above the wheat crop ranged from 0 at sunrise to near 14°C around solar noon on both Days 99 and 100. As a result, the operating dewpoint temperature exceeded the range for which the analyzer was calibrated and resulted in overranging and questionable data around midday of Day 99. There was no overranging observed with the CO_2 data.

An infrared thermometer (IRT_c) (Teletemp Model AG42) for chamber associated canopy temperature (CT_c) measurements was mounted on the outside front corner of the chamber and pointed at an oblique angle to a spot approximately 3 m directly in front of the chamber. The IRT_c had a 4° (FOV) so that the spot size when the chamber was lowered was approximately 0.15 m in diameter. The CT_c represents the mean of the 15 measurements during the 30-s calculation window while the chamber is in the DOWN position. The air temperature (TA) was measured inside the chamber in a ventilated shielded cylinder and may not reflect the true ambient temperature. Typically this temperature will be 1–2°C warmer than ambient temperature because of its location in the chamber and the impact of the chamber on internal microclimate. The TA associated with IRT_c chamber data was the initial value prior to lowering the chamber.

The chamber sampling sequence was a measurement at least once an hour on each of the plots to minimize plant damage and any possible chamber effects. The sequence was started with a deficit-irrigated plot, followed by a fully irrigated plot, on the hour. The second cycle was started by measuring the next deficit-irrigated plot 20 min later, followed by the second irrigated plot. This cycle was repeated at 20-min intervals so that each plot was measured at least once an hour using the three replicates.

The CER will be referred to as the gas exchange without correction for soil respiration (g CO_2 m^{-2} h^{-1}). Soil respiration measurements were made within 1 m of the corner of the portable chamber locations in each of the six plots on 9 April 1989 and showed no diurnal trend. The daily average soil respiration was 0.22 g CO_2 m^{-2} h^{-1} and 0.33 g CO_2 m^{-2} h^{-1} on the deficit and fully irrigated plots, respectively (Francis Nakayama, personal communication, 1989). These low values represent only 7% of the maximum CER measured and as a result will be neglected. The site for soil respiration measurements was a small open area with no plants growing within the cylinder. The same soil location was used for soil respiration, even though the portable chamber was moved to new locations on 10 April 1989.

Portable chamber CER and ET, as well as the other microclimate parameters measured, were linearly interpolated to the time of aircraft overpasses. Variability in measured values represents spatial variability and

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

experimental error. Solar radiation and photosynthetically active radiation measured at the chamber may be slightly erratic due to the sensors not being perfectly level for each measurement.

A second measure of canopy temperature (CT_m) was obtained at a standard microclimate station located near the center of fully irrigated wheat in Field 3201 shown in Figure 1. The central location of the microclimate station gave about 140 m of fetch to the north and south and more than 500 m to the east and west. The meteorological station consisted of a standard tripod tower, an auxiliary sensor support tower, a data logger, attendant sensors, and magnetic tape data storage. The infrared thermometer (IRT_m) was an Everest model 4009 with a 15° FOV that was mounted at 1.5 m above the wheat canopy and oriented to provide a nadir view of the canopy surface during the two days of this study. The IRT_m data was recorded on an automatic data logger in association with net radiation, solar radiation, air temperature, relative humidity, vapor pressure deficit (all at 1.5 m above canopy), soil heat flux, and soil temperature at 1 min intervals during the day for all of 9 April and up to 1600 hours on 10 April 1989. Saturation vapor pressure was calculated from air temperature using the formula of Tetens (1930). Reference ET (ET_r) was calculated from the microclimate data after Snyder and Pruitt (1985) with an adjustment for the growth stage of wheat.

Land-based measurements of canopy temperature were compared with remotely sensed canopy temperature to provide a better understanding of field-scale spatial variability. Airborne sensors were used to measure reflected radiation and surface temperatures (CT_a) of the wheat canopy along a transect through the middle of Field 3201 and 3202. The airborne sensors included an Exotech radiometer (with the SPOT HRV multispectral and panchromatic filters), an infrared thermometer (IRT_a), a color video camera, and a multispectral video camera. There were two groups of aircraft measurements each day about 1 h apart with each group consisting of an east-to-west and a west-to-east flight over the field. The aircraft was flown at a nominal altitude of 150 m above ground level, with that elevation resulting in a spot size of about 40 m. Information from video tapes was used to identify ground location and target composition for each spectral data sample. Instruments were installed on a mount that could be positioned to provide a view normal to the ground surface. A small data logger signaled the device to collect a sample every second, and recorded the time of sampling to 0.0001 h.

Remote Estimation of Evaporation

Estimates of instantaneous, hourly, and daily ET were derived from aircraft-based measurements of surface radiance and ground-based meteorological data. This procedure has been described in detail by Jackson (1984), Jackson et al. (1983; 1985; 1987), and Moran et al. (1989). It is based on the evaluation of the energy balance equation, that is,

$$LE = R_n - G - H,$$

where LE is the latent heat flux density [a product of the heat of vaporization L (J kg^{-1}) and the rate of evaporation E (kg s^{-1} m^{-2})], R_n is the net radiant flux density, G is soil heat flux density and H is sensible heat flux density. All terms in Eq. (1) are in units of W m^{-2} and values of LE, G, and H are positive when directed away from the surface.

The remote method, on a local scale, had the surface-dependent components of the energy balance (reflected radiation and surface temperature) evaluated remotely and combined with meteorological components (solar and sky radiation, air temperature, wind speed, and vapor pressure) to evaluate the energy balance components (R_n, G, and H) over agricultural areas. R_n is the sum of incoming and outgoing radiant flux densities. Incoming solar radiant flux density was measured with a calibrated pyranometer and incoming longwave radiant flux density estimated from ground-based measurements of air temperature and vapor pressure using the Stephan–Boltzman equation (Brutsaert, 1975). The outgoing R_n components was obtained from data collected with downlooking multispectral sensors (Jackson, 1984). A relation between G/R_n and spectral data in the red and near-infrared (NIR) wavebands was determined where $G/R_n = 0.583e^{-2.13\text{ND}}$ and ND is the normalized difference $[(P_{\text{NIR}} - P_{\text{red}})/(P_{\text{NIR}} + P_{\text{red}})]$. The sensible heat flux density H can be expressed as $H = \rho C_p (T_s - \text{TA})/r_a$, where ρC_p is the volumetric heat capacity (J m^{-3} C^{-1}), T_s and TA are surface and air temperature, and r_a is the stability corrected aerodynamic resistance (s m^{-1}), which is dependent on plant height, T_s, TA, and wind speed (Moran et al., 1989).

The meteorological components were measured at 1-min intervals averaged for 0.5 h as described earlier. Instantaneous values of LE (LE_i) were estimated based on these data along the transect. Daily ET was calculated from LE_i as a function of R_{ni}/R_{nd}, assuming the day was cloud-free and wind speed remained relatively constant over the daylight period (Jackson et al., 1983). Aircraft values of ET in Tables 1 and 2 are energy balance estimates for a single pixel closest to the portable chamber plots on the flight line. In Field 3201, data points were located as closely as possible to the designated fully irrigated and deficit irrigated borders; however, the diameter of an aircraft-based pixel (40 m) was larger than the width of a single border (about 28 m) and the pixel often partially covered adjacent borders. Single CT_a values were compared with CT_c which represent averages of three replicates. Evapo-

Table 1. Instantaneous Values of Canopy Temperature, Canopy Photosynthesis and Evapotranspiration at Times Closest to Aircraft Measurements

DY	Sensor Location	CER ($g m^{-2} h^{-1}$)	ET ($mm h^{-1}$)	Canopy Temp. (°C)	Air Temp. (°C)
99	Deficit irr. at 10.44 h				
	Chamber[a]	0.83	1.11	27.50	34.01
	Aircraft[b]	—	1.25	25.15	—
99	Deficit irr. at 11.30 h				
	Chamber	1.75	1.28	28.13	34.68
	Aircraft	—	1.00	28.03	—
99	Full irr. at 10.44 h				
	Chamber	3.81	1.21	27.03	34.03
	Aircraft	—	1.40	24.08	—
	Weather station	—	—	23.14	30.67
99	Full irr. at 11.30 h				
	Chamber	4.30	1.26	27.70	35.06
	Aircraft	—	1.00	28.18	—
	Weather station	—	—	26.22	32.98
100	Deficit irr. at 10.23 h				
	Chamber	2.46	0.58	24.90	26.93
	Aircraft	—	0.90	23.33	—
100	Deficit irr. at 11.05 h				
	Chamber	2.36	0.59	25.67	27.86
	Aircraft	—	1.05	25.70	—
100	Full irr. at 10.23 h				
	Chamber	3.84	0.58	25.17	27.16
	Aircraft	—	0.90	23.13	—
	Weather station	—	—	23.28	28.00
100	Full irr. at 11.05 h				
	Chamber	4.29	0.67	25.60	27.73
	Aircraft	—	1.00	25.77	—
	Weather station	—	—	23.74	28.75

[a] Chamber data were averaged for the three replicates (benches) closest to aircraft overpasses.
[b] East and west overpasses were within 2 mins of each other with little difference and thus represent the average of the flight times.

Table 2. Summary of Total Daytime Values of Canopy Photosynthesis (CER) and Evapotranspiration (ET) for Wheat Estimated from Chamber and Aircraft Data[a]

	9 April 1989[b] (Day 99)				10 April 1989 (Day 100)			
	Chamber		Aircraft	Reference[c]	Chamber		Aircraft	Reference
Irrigation and Plot	CER ($g m^{-2}$)	ET (mm)	ET (mm)	ET (mm)	CER ($g m^{-2}$)	ET (mm)	ET (mm)	ET (mm)
Deficit-1	10.69	10.50			11.50	7.67		
Deficit-2	11.36	10.41			20.10	7.86		
Deficit-3	0.85	10.57			10.02	7.55		
Average	7.63	10.49	10.53	—	13.87	7.69	8.88	—
Full-1	24.18	10.95			27.70	8.26		
Full-2	26.83	10.81			28.75	8.32		
Full-3	31.15	11.94			30.33	8.66		
Average	27.39	11.23	11.18	10.67	28.93	8.41	8.93	8.91

[a] Only positive values of CER were included. Chamber ET was extrapolated to 0 at 0600 and 1900 h which approximated sunrise and sunset.
[b] Note chamber values on Day 99 are not reliable due to generator failure in the afternoon.
[c] Reference ET was calculated from weather station data.

transpiration from aircraft data were compared with chamber data integrated from sunrise to sunset.

RESULTS AND DISCUSSION

Microclimate data collected in the fully irrigated wheat field are summarized in Figures 2 and 3 for Days 99 and 100, respectively. Both days were cloud-free, with solar radiation of 27.8 MJ m^{-2} d^{-1} and 27.9 MJ m^{-2} d^{-1} and maximum air temperatures of 37.0° and 36.3°C for Days 99 and 100, respectively. Both days showed relatively smooth diurnal trends. The largest difference between the two days was in wind velocity and direction. On Day 99 the wind was from the south and west with velocities that varied from 2 m s^{-1} to 5 m s^{-1}, while, on Day 100, the largest velocity was about 2 m s^{-1} from the north and east early in the day shifting to the west late in the day. Canopy temperature (CT_m) at the weather station showed slightly wider fluctuations on Day 99 that corresponded to wind and vapor pressure deficit fluctuations. Daily reference ET (ET_r) calculated from the microclimate data was 10.7 mm d^{-1} and 8.9 mm d^{-1} for Days 99 and 100, respectively, reflecting the daily mean vapor pressure deficit of 3.4 kPa and 2.9 kPa.

Diurnal trends in CER and ET for fully irrigated and deficit-irrigated plots are summarized in Figures 4 and 5 for Days 99 and 100, respectively. The trend lines in these figures were "eye-fitted" through the data points. High evaporative demand was evident on Day 99. Equipment failure interrupted data collection for about 3 h; thus all chamber data on Day 99 must be interpreted with caution due to absence of complete afternoon data. Daily estimates were obtained using linear interpolation for the missing data, and the maximum ET just prior to solar noon was the same magnitude reported for alfalfa by Van Bavel (1966) with a precision-weighing lysimeter at nearby Phoenix, Arizona under a similar climate. The small difference in ET between the deficit and fully irrigated plots was larger on Day 99 than on Day 100, possibly related to the chamber plots being closer to the edge of the field.

Results from Day 100 show a smooth diurnal trend in CER and ET with some scatter due to replicate variation (Fig. 5). Both CER and ET show a similar relationship starting with low values just after sunrise with maximum values around solar noon. The maximum CER was 5 g m^{-2} h^{-1} on the fully irrigated plots in agreement with Iwaki et al. (1976), Morgan (1988), and Puckridge (1971). Of interest is the magnitude of plant

Figure 2. Summary of the microclimate data over the fully irrigated wheat on 9 April 1989 (Day 99).

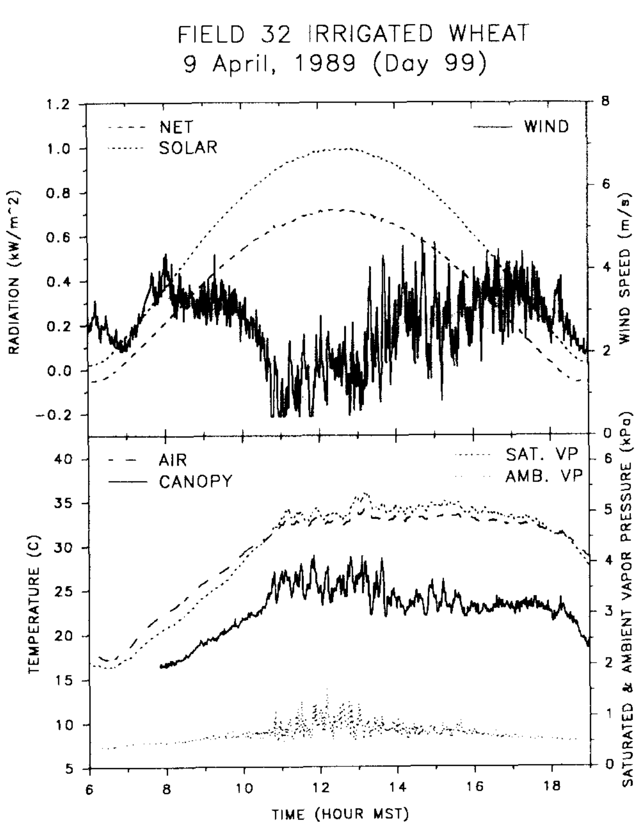
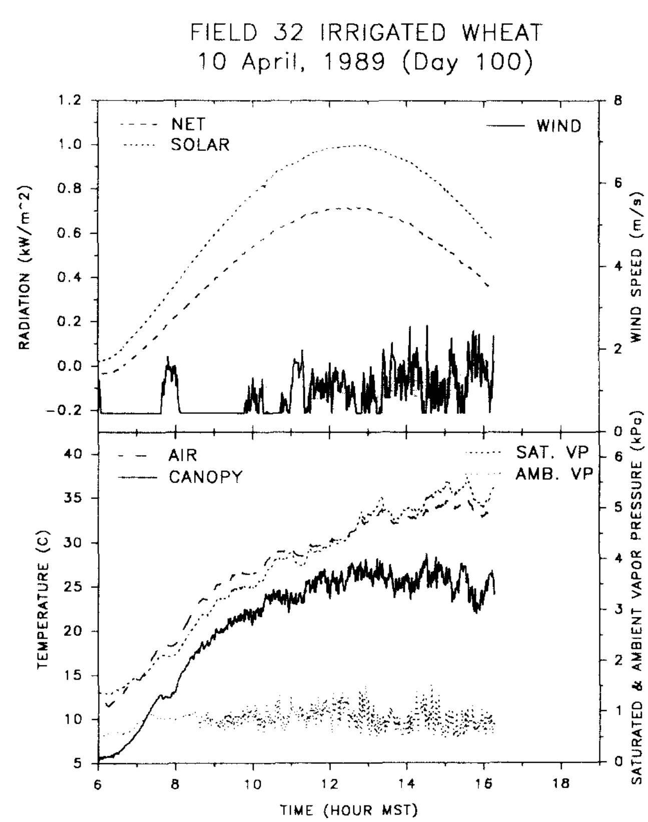


Figure 3. Summary of the microclimate data over fully irrigated wheat on 10 April 1989 (Day 100).



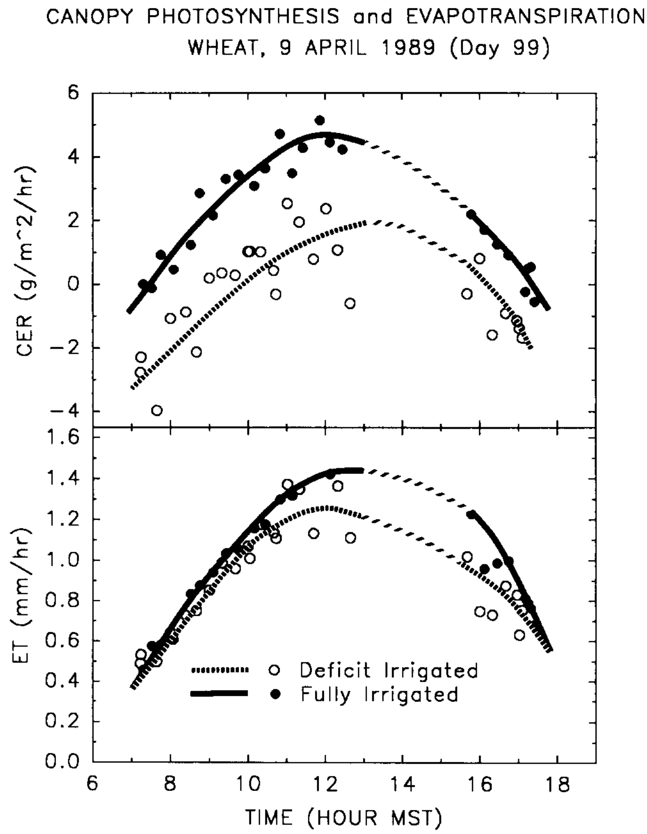


Figure 4. Canopy photosynthesis and evapotranspiration as a function of time for the deficit and fully irrigated plots on Day 99. Note: missing data in the afternoon as a result of equipment failure.

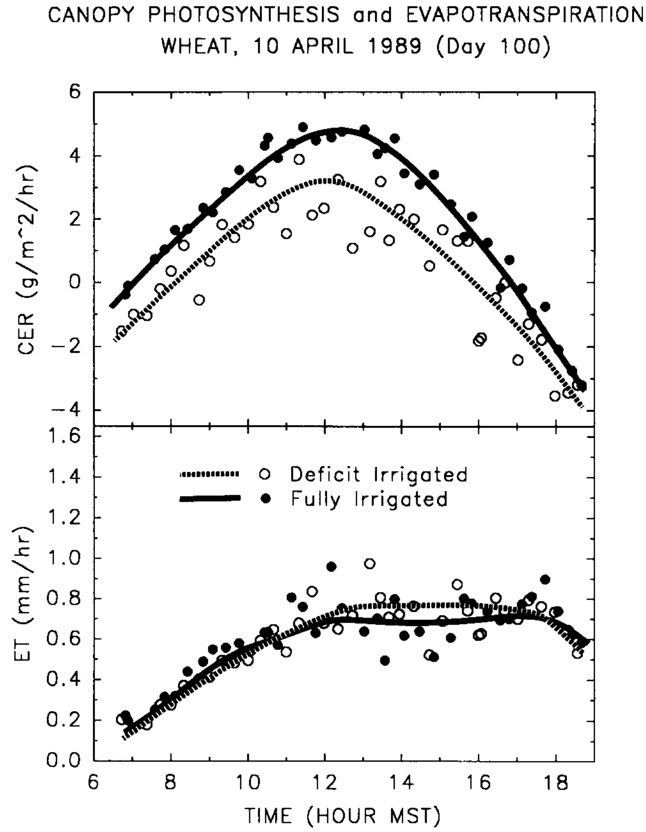


Figure 5. Canopy photosynthesis and evapotranspiration for the deficit and fully irrigated plots on Day 100.

respiration near sunset. Both deficit and fully irrigated plots had CER values as low as -3.5 g m^{-2} h^{-1} before sunset, while CT and ET were still relatively high. The difference in CER on deficit and fully irrigated treatments was consistent but smaller than those on Day 99. The differences in ET were similar and smaller than differences in CER for both days. This disparity suggests wheat CER is more sensitive to water stress than ET. Similar results were obtained by Johnson et al. (1981a, b), who found a decline in apparent photosynthesis when values of ET were high. They noted wheat CER and ET were often independent, suggesting factors other than stomatal closure were important in determining CER.

On Day 99, CT and TA as measured with the portable chamber were as much as 3°C higher than the corresponding temperatures measured at the weather station and had parallel diurnal trends (Fig. 6). These CT_c data represent only those from the fully irrigated plots so that they are directly comparable with the microclimate station (CT_m). While trends for the absolute values of CT from the chamber and microclimate station were similar, CT – TA showed nearly the same magnitude from -4°C early to -10°C around midday, for both methods. Both chamber and weather station data showed considerable variation over time that may be related to the viewing angle. The weather station reflects temporal variability as a result of wind action and vapor pressure deficit on the canopy and the chamber data reflect both temporal and spatial variability across the three replicates. Part of the difference on Day 99 between the trends in CT_c and CT_m data could possibly be to the direction of the wind. The hot, dry winds coming across the bare soil to the south may have brought advective energy that affected canopy temperature and chamber measurements more because of their close proximity to the south edge of the field (Davenport and Hudson, 1967; Dugas and Bland, 1989).

On Day 100, the wind was from the north and west so that the south edge of the field was seeing a well-irrigated fetch and as a result there was closer agreement between CT and TA as measured by the portable chamber and the weather station (Fig. 7). The CT_c was just slightly above CT_m with similar diurnal trends. Both CT – TA differences showed the same trend; however, IRT_m showed a larger difference earlier in the morning with better agreement between methods in the afternoon. Part of the difference may be related

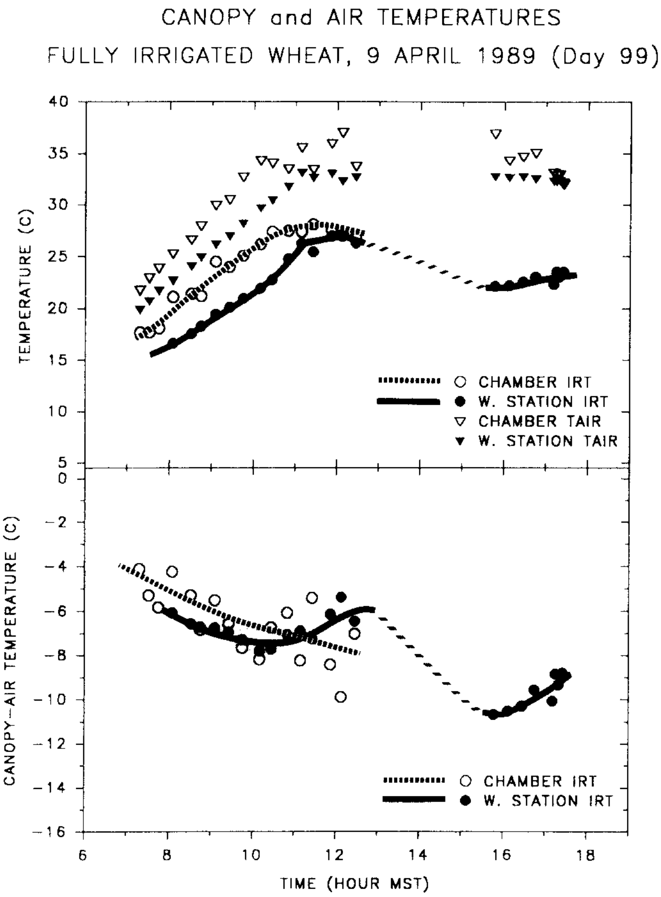


Figure 6. Canopy and air temperature from the chamber and weather station for the fully irrigated wheat and canopy temperature minus air temperature difference on 9 April 1989.

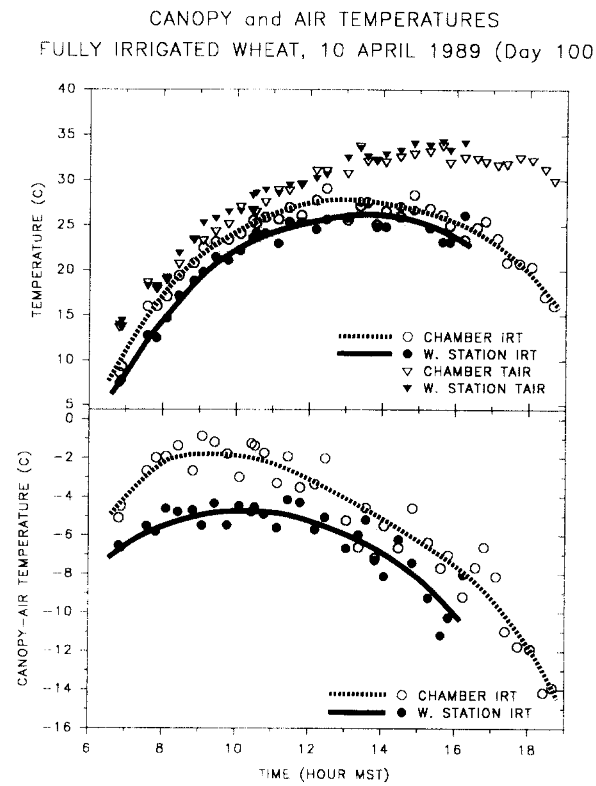


Figure 7. Canopy temperature and air temperature from the chamber and weather station for the fully irrigated wheat and canopy temperature minus air temperature difference on 10 April 1989.

to the lack of aspiration on the weather station air temperature and the interior location of the chamber air temperature sensor. There was a decline in CT − TA throughout the day for both systems.

The relationship between CER and ET relative to $CT_c - TA_c$ was of interest. When ET was plotted as a function of $CT_c - TA_c$ for Day 100, the data points were scattered and showed a small amount of hysteresis on the hydration and dehydration part of the cycle (Fig. 8). Both the deficit and fully irrigated plots showed the same diurnal trend with negligible difference in the ET vs. $CT_c - TA_c$ relationship. At a given $CT_c - TA_c$, ET was lower in the morning than in the afternoon due to vapor pressure deficit and slightly higher winds. The scatter in the data suggests the need for caution in interpreting these results; however, the data do show a nonlinear relationship between ET and CT_c.

Canopy photosynthesis for both irrigation levels showed the same diurnal trends for Day 100 (Fig. 9). For a given $CT_c - TA_c$ there were two values of CER, depending on whether the measurements were made during morning or afternoon. Canopy photosynthesis increased with increasing $CT_c - TA_c$ until about midday and then decreased as the CER declined with the afternoon decrease in radiation. Fully irrigated and deficit-irrigated wheat showed essentially the same relationship with the deficit-irrigated being slightly offset due to lower CER values. These results point out the importance of knowing the time of day and microclimate data when comparing CT and CER.

Early on Day 100, CER was negative, indicating plant respiration, up to about 0700 h and then increased to a midday maximum. A rapid decrease in CER and substantial respiration were measured prior to sunset. The CER was approximately -3.5 g CO_2 m^{-2} h^{-1} at 1830 h. The poor correlation between CT_c and canopy respiration late in the day suggests a limitation in using CT to evaluate plant performance throughout the entire day.

Using remote sensing techniques to calculate wide area CER using CT is further complicated by spatial variability. Canopy temperatures measured from the aircraft on the west to east passes only are summarized in Figure 10. Similar trends were observed on the east to west passes (data not shown). Immediately evident

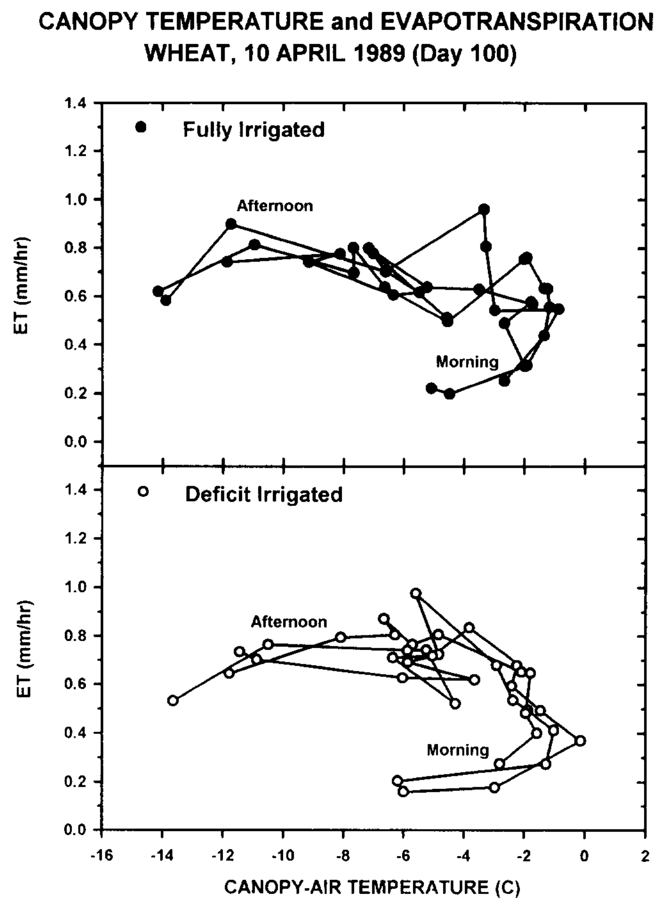


Figure 8. The relationship between evapotranspiration and canopy temperature on fully irrigated and deficit-irrigated wheat on 10 April 1989.

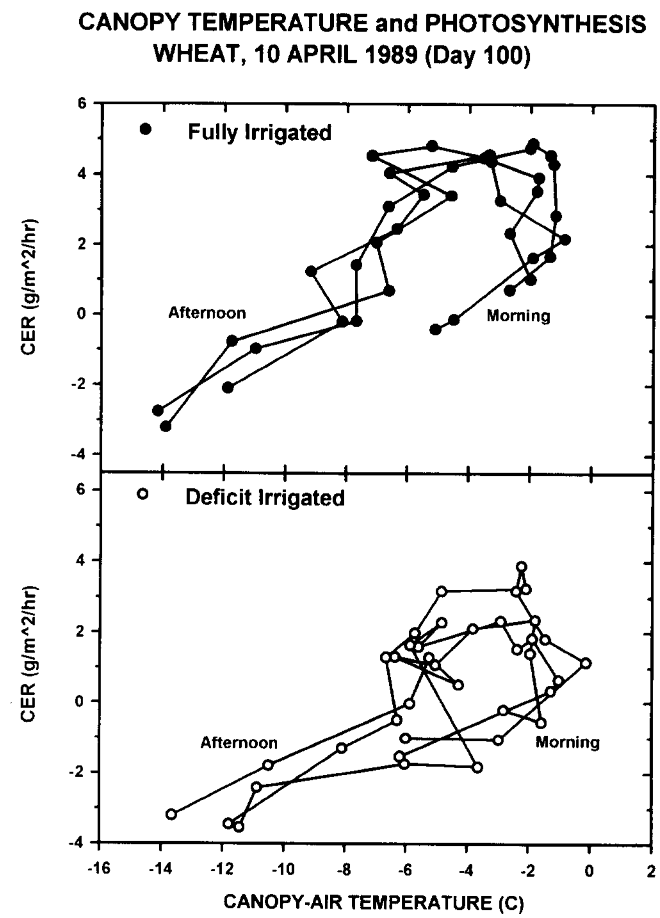


Figure 9. The relationship between canopy photosynthesis and canopy temperature on fully irrigated and deficit-irrigated wheat on 10 April 1989.

is the higher CT at the east end of Field 3202 due to wheat in that area near maturity. Spatial variation along the uniformly irrigated wheat in Field 3201 was slightly larger on Day 99 than Day 100, apparently due to the change in canopy reflectance caused by higher wind speeds. The limited data did not allow firm conclusions about soil-induced differences in CT. However, the temporal variation on the uniformly irrigated wheat showed larger differences than spatial variation along the transect at any one point in time. The average difference for the west to east passes between the first group ($\approx$ 10 h) and the second group ($\approx$ 11 h) of measurements was 2.6°C on Day 99 and 2.2°C on Day 100 related to different microclimate conditions. These temporal fluctuations, while only representing two points in time each day, are in general agreement with more frequent and detailed ground based measurements of CT.

The instantaneous values of CT, CER, and ET at times closest to the aircraft measurments are summarized in Table 1. The largest difference in CT was between days, with Day 99 warmer as reflected in CT and TA. The agreement between the various methods was only marginal and differed by as much as 4°C when the measurements were taken nearly simultaneously. The CT_c may reflect spatial variability from advective energy on Day 99 as a result of the chamber being close to the south edge of the plots. On Day 100, ET by both chamber and aircraft may reflect spatial variability. The lower chamber ET may have been due to advective energy that had dried the south edge of the field the previous day. The consistent trends with aircraft measurements suggests reasonable values for the middle of the field. Both the chamber and the aircraft estimates of ET were higher on Day 99 and lower on Day 100 in relation to the evaporative demand primarily determined by reference ET, TA, and vapor pressure deficit and partly as a result of a change in advection related to change in the wind direction.

Estimates of aircraft daily ET were large on 9 April in the irrigated wheat field (Table 2). On this date, the evaporation rate from the irrigated field was stimulated by strong winds and high air temperature as reflected in the higher reference ET on Day 99. Even so, values

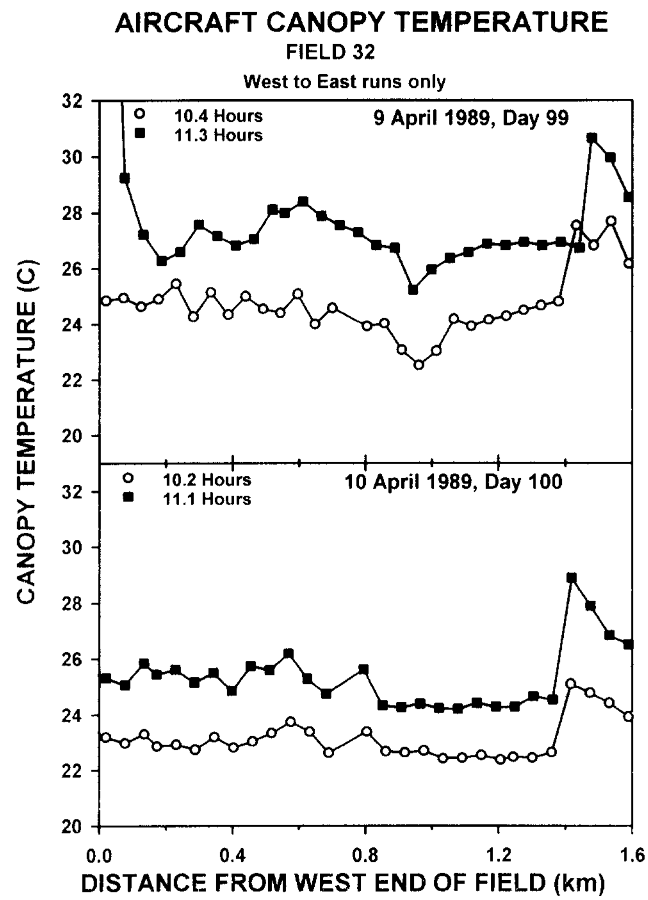


Figure 10. Canopy temperature along the west to east transects across Field 32 measured from the aircraft on 9 and 10 April 1989.

of ET greater than 11 mm d^{-1} need to be interpreted with caution. Previous work for alfalfa using a precision lysimeter showed up to 12 mm d^{-1} was possible (Van Bavel, 1966). The magnitude of the sensible heat flux density (*H*) values was extraordinarily large in these fields on 9 April, due largely to the high wind speeds resulting in low aerodynamic resistance.

The integrated values of CER and ET obtained by the chamber are compared with reference ET and aircraft estimates in Table 2. There was considerable variation between the replicates of the deficit-irrigated and reasonable agreement on the fully-irrigated plots. The large differences between Day 99 and Day 100 are evident; however, Day 99 chamber results are only qualitative due to missing data when the equipment failed. The aircraft values represent the average of the four passes on a given day. Values for fully irrigated plots agree reasonably well with ET_r calculated from microclimate data. The mean values of the daytime ET were less than those reported by Johnson et al. (1981a,b) and showed only 8.5% reduction on the deficit-irrigated plots suggesting only a slight stress. These daily values show reasonable agreement in view of the difference and limitations of the methods, but are slightly larger than those reported by Dugas et al. (1991) obtained using Bowen ratio and eddy correlation techniques on the same plots.

On Day 100, the daytime total CER showed considerable difference between fully irrigated and deficit-irrigated treatments. The average for the three irrigated plots was 28.9 g m^{-2} similar to daytime totals reported by Johnson et al. (1981a,b). Deficit irrigated plots showed a 52% reduction in CER, suggesting a significant stress on Day 100.

In summary, these preliminary results suggest caution in using remote sensing to measure and relate CT to CER and ET throughout the day. Both CER and ET data showed reasonable diurnal trends and magnitudes for wheat at this stage of development and leaf area index. The relatively high plant respiration near sunrise and sunset confirms that CER is very dynamic and requires both day and nighttime measurements to accurately integrate over an extended period. The differences in CER between fully irrigated and deficit-irrigated plots suggested some stress. The small differences between fully irrigated and deficit-irrigated ET values needs further investigation. However, general agreement between the aircraft- and chamber-measured values on Day 100 is encouraging.

The diurnal trends in CT were only partially related to the diurnal trends in CER and ET. At any given $CT_c - TA_c$, CER was higher in the afternoon than in the morning. While the relationships for ET and $CT_c - TA_c$ were not as distinct, the relationship between CER and $CT_c - TA_c$ showed a distinct loop apparently related to dehydration and rehydration of the plants where the late afternoon values of CER were significantly lower. Similarly for ET, morning values at the same $CT_c - TA_c$ were lower than afternoon values. Both irrigated and deficit-irrigated plots showed essentially the same trend with the deficit-irrigated plot having smaller CER. The temporal variation in CT followed expected trends based on the microclimate data. The spatial variation of irrigated wheat CT measured from the aircraft was larger on a windy day, apparently related to changes in canopy surface characteristics. Chamber and airborne estimates of daily ET showed reasonable agreement despite methods and scale differences. These results suggest caution in inferring plant performance measured as canopy photosynthesis or ET from canopy temperature alone. Utilization of remote sensing techniques may require additional data to develop a method that allows estimation of canopy photosynthesis from canopy temperature.

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REFERENCES

Brutsaert, W. H. (1975), On a derivable formula for long-wave radiation from clear skies, *Water Resour. Res.* 11:742–744.

Davenport, D. C., and Hudson, J. P. (1967), Local advection over crops and fallow. I. Changes in evaporation rates along a 17-km transect in the Sudan Gezira, *Agric. Meteorol.* 4: 339–352.

Dugas, W. A., and Bland, W. L. (1989), Effect of bordering soil surface moisture conditions on evaporation from soybean, *Field Crop Res.* 21:161–166.

Dugas, W. A., Fritschen, L. J., Gay, L. W., et al. (1991), Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat, *Agric. For. Meteorol.* 56:1–20.

Iwaki, H., Takeda, G., and Udagawa, T. (1976), Ecological studies on the photosynthesis of winter cereals. II. Photosynthesis of wheat and rye plants under field conditions, *Proc. Crop Sci. Soc. Jpn.* 45(1):32–39.

Jackson, R. D. (1984), Total reflected solar radiation calculated from multiband sensor data, *Agric. For. Meteorol.* 33:163–174.

Jackson, R. D., Hatfield, J. L., Reginato, R. J., Idso, S. B., and Pinter, P. J., Jr. (1983), Estimation of daily evapotranspiration from one time-of-day measurements, *Agric. Water Manage.* 7:351–362.

Jackson, R. D., Pinter, P. J., and Reginato, R. J. (1985), Net radiation calculated from remote multispectral and ground station meteorological data, *Agric. For. Meteorol.* 35:153–164.

Jackson, R. D., Moran, M. S., Gay, L. W., and Raymond, L. H. (1987), Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data, *Irrig. Sci.* 8:81–90.

Johnson, R. C., Witters, R. E., and Ciha, A. J. (1981a), Daily patterns of apparent photosynthesis and evapotranspiration in a developing winter wheat crop, *Agron. J.* 73:414–418.

Johnson, R. C., Witters, R. E., and Ciha, A. J. (1981b), Apparent photosynthesis, evapotranspiration, and light penetration in two contrasting hard red winter wheat canopies, *Agron. J.* 73:419–422.

Meyer, W. S., Reicosky, D. C., Barrs, H. D., and Shell, G. S. G. (1987), A portable chamber for measuring canopy gas exchange of crops subject to different root zone conditions, *Agron. J.* 79:181–184.

Moran, M. S., Jackson, R. D., Raymond, L. H., Gay, L. W., and Slater, P. N. (1989), Mapping surface energy balance components by combining Landsat Thematic Mapper and ground-based meteorological data, *Remote Sens. Environ.* 30:77–87.

Morgan, J. A. (1988), Growth and canopy carbon dioxide exchange rate of spring wheat as affected by nitrogen status, *Crop Sci.* 28:95–100.

Peters, D. B., Clough, B. F., Garves, R. A., and Stahl, G. R. (1974), Measurements of dark respiration, evaporation, and photosynthesis in field plots, *Agron. J.* 66:460–462.

Puckridge, D. W. (1971), Photosynthesis of wheat under field conditions. III. Seasonal trends in carbon dioxide uptake of crop communities, *Aust. J. Agric. Res.* 22:1–9.

Reicosky, D. C. (1985), Advances in evapotranspiration measured using portable field chambers, in *Advances in Evapotranspiration. Proc. National Conference on Advances in Evapotranspiration*, ASAE Pub. 14-85, 16–17 Dec., Chicago, pp. 79–86.

Reicosky, D. C. (1990), Canopy gas exchange in the field: closed chambers, *Remote Sens. Rev.* 5(1):163–177.

Reicosky, D. C., and Peters, D. B. (1977), A portable chamber for rapid evapotranspiration measurements on field plots, *Agron. J.* 69:729–732.

Reicosky, D. C., Sharratt, B. S., Ljungkull, J. E., and Baker, D. G. (1983), Comparison of alfalfa evapotranspiration measured by a weighing lysimeter and a portable chamber, *Agric. Meteorol.* 28:205–211.

Reicosky, D. C., Wagner, S. W., and Devine, O. J. (1990), Methods of calculating CO_2 exchange rates for corn and soybean using a portable field chamber, *Photosynthetica* 24(1):22–38.

Snyder, R., and Pruitt, W. (1985), Estimating reference evapotranspiration with hourly data, in *California Irrigation Management Information System Final Report, June 1985, Vol. II. Land, Air and Water Resources Papers #100013-B* (R. Snyder et al., Eds.), Univ. of California, Davis, Chap. VIII.

Tetens, O. (1930), Über einige meteorologische Begriffe, Z. *Geogr. Phys.* 6:297–309.

Van Bavel, C. H. M. (1966), Potential evaporation: The combination concept and its experimental verification, *Water Resource. Res.* 2:455–467.